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Ballistic Electron Transport Studies Using BEEM
Report on ONR Grant No. N00014-92-J-1277

by

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We started work on this grant in the Spring semester of 1992. The grant allows support for one graduate student who currently is Bruce Turner. Mr. Turner is now starting his third year at Rensselaer and his second year with me working on BEEM related projects and is making satisfactory progress toward his Ph.D. in Physics. He completed his last required course in the fall of 1992 and will take his candidacy in June of 1993. I expect that he will receive his Ph.D. in the 94/95 academic year.

Dr. Ed Lee joined our effort as a post-doc starting May 15. Ed had completed his Physics Ph.D. on "Study of ballistic carrier transport using BEEM," in my group and has agreed to continue working on this project for one year. He departed my group on May 10 to join Dr. von Kanel's group at ETH in Zurich, Switzerland, where he will assist with the set up of a BEEM program there. We were very fortunate to have Ed; he won the Huntington Award from the Physics Department faculty for his outstanding graduate work and has been instrumental in establishing our current effort in BEEM. I expect to hire a new post-doc in June of 1993 and am currently working from a short list of four outstanding candidates.

Most of the effort the first year of this program has been devoted to the building of required instrumentation. The thin metal films required for this work necessitated having a feed-back controller for the multi-hearth electron beam evaporator in the MBE system. Thus, one of our initial projects under this grant was the installation of a Inficon Sentinel controller in the MBE system. This project has been successfully competed. The new electron beam evaporator, with its controller, will allow us to evaporate Pt or Au and Ge in the deposition chamber in addition to Si and Co which were already available. We have started MBE growth of SiGe alloys with a new student (Byong Kim) and expect to start BEEM studies of metal layers on SiGe alloys this summer.

A key part of this project is the ultra-high vacuum (UHV) BEEM studies of MBE grown material. After debating the alternatives, we have decided to install the UHV STM directly into the MBE chamber after testing it in air. This eliminates the problem with sample transfer between the MBE system and the STM station and we believe that we have an STM design that will result in minimum interference with the MBE machines normal operation. A significant cost of the STM are the two Burleigh inchworms for the STM tip and for the (base) metal contact. The inchworms and their control electronics cost a total of $11355. We have designed and constructed the other electronics for operation of the STM in the BEEM mode. The microscope assembly itself has also been completed. In addition, all the hardware necessary to install the STM/BEEM system into the MBE system has been purchased and is currently being assembled. Successful tunneling has been demonstrated with the new microscope although we are currently having some trouble with our BEEM amplifier. A more detailed summary of progress on the UHV STM is attached as Appendix A. Our total capital equipment costs have come out to be approximately $36,500 which exceeds our budget request by 3%.

We have also continued our BEEM studies using the existing STM set-up. The lack of any "search-light" effect in the Au/Si system seems to definitively rule out simplistic ballistic transport in the Au in favor of diffusive transport. We have performed detailed Monte-Carlo calculations which model our experimental results very well. These calculations and results have been written up for publication and were presented at the AVS meeting in October of 1992, and at the BEEM Workshop and PCSI meeting in January of 1993. A list of publications is attached. We feel that multiple elastic scattering dominates BEEM measurements on Au/Si unless something is done to "absorb" (inelastically scatter electrons) at the metal/semiconductor interface. This may already be occurring at some of the other metal/semiconductor systems that have been reported although we also believe that there are some inconsistencies in the way that the BEEM community is presently reporting its results. The only way this issue will be resolved is for more studies to be completed on more metal/semiconductor systems (particularly single crystal metal/semiconductor systems) and for an improved evolution of the theory.

Our work thus far has convinced us that low temperature BEEM is necessary to study many interesting samples due to the need to increase the effective resistance between the metal (base) layer and the underlying semiconductor (collector). For this reason, we have also invested substantial effort this year in modifying our current BEEM set-up to allow studies in liquid nitrogen inside a dry box. A principal problem that we encountered was that our laboratory on the second story of the Low Bldg. was becoming increasingly noisy due to the activities of some of the neighboring labs. This was making BEEM images increasingly difficult to take. Therefore, we recently moved the BEEM laboratory to the basement of Science Center where building vibrations are substantially reduced. Progress on the low temperature STM is attached as Appendix B.

<u>Plans for the Current Year</u>:

1.) Complete construction and testing of UHV STM and install into the MBE system.

2.) Continue BEEM measurements of epitaxial $CoSi_2$ layers and Au on Si(100) and SiGe/Si substrates.

3.) Initiate BEEM studies of metal/epitaxial CaF_2/Si systems.

4.) Continue ac BEEM studies of inelastic scattering channels; particularly in the new systems and with better spatial resolution.

<u>Goals</u>:

1.) Demonstrate the role of elastic scattering at the metal/semiconductor interface.

2.) Demonstrate resonant transmission with the CaF_2/Si system.

3.) Attempt to identify defects (ie. grain boundaries) associated with inelastic scattering channels.

Papers published or submitted acknowledging this *Contract:*

"Imaging of metal/semiconductor interface by ballistic-electron-emission microscopy (BEEM)," E.Y. Lee, B.R. Turner, J.R. Jimenez, and L.J. Schowalter, to be publ. MRS Proc., Fall MRS Meeting, Boston, Dec., 1992, (MRS, Pittsburgh, 1993).

"Diffusive and inelastic scattering in ballistic-electron-emission spectroscopy and ballistic-electron-emission microscopy," E.Y. Lee, B.R. Turner, L.J. Schowalter, and J.R. Jimenez, to be publ. J. Vac. Sci. Technol. (1993).

Appendix A

UHV STM Progress & Plan

Category	Component	Status
Electronics	Tunnel amplifier & feedback controller	completed & tested
	BEEM amplifier	completed & tested
	Inchworm controllers	received & tested
Hardware	STM head	completed & tested (successful tunneling)
	Wiring-to-feedthru adapter	incomplete
	Head-to-feedthrough adapter	incomplete
Vacuum Equipment	Linear feedthrough	all received
	Wobble stick	
	Adapter flange	
Software	DAC/ADC interfacing	adapted LT STM programs
	DAC/ADC interfacing (new boards)	incomplete (currently using control boards for LT STM)
	Inchworm control	incomplete
	Spectroscopy programs	adapted LT STM programs
	Microscopy programs	incomplete

The STM has successfully tunneled in air using a gold tip at a tip bias of .1V, with tunnel current noise <10mV, while floating on an optical table. Tunnel current starts to oscillate at higher tip bias voltages, probably indicating that some modifications to the control electronics are necessary (gain needs to be reduced).

The BEEM amplifier has been tested and appears to function properly (bias may be adjusted, and test voltages are amplified properly).

Appendix B

LT STM Progress & Plan

Category	Status
STM Head	functions properly in air and has been used for room temperature studies of Au/Si (100)
	has been modified for operation at 77K
Control Electronics	operational: have been previously used for room temperature studies of Au/Si (100)
Glove Box	completed & tested; can be purged with Argon or Nitrogen gas prior to introduction of liquid Nitrogen.
Control Software	has been used for operations at both room temperature and at 77K
	Some software has been adapted for the UHV STM

The microscope and glove box were recently transferred to another lab to avoid vibration problems inherent in our original lab. The equipment has been set up in the new lab, and has been tested to insure that no damage was inflicted during the moving process.

The microscope appears to have some problems from thermal expansion; unless the coarse and fine adjusts are set to maximize their travel ranges, the sample tends to move out of range of the tip when the microscope is immersed in liquid N_2. This problem can be compensated for with careful setup, but some more foolproof mechanism should be developed.